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Micromix combustor for high temperature hybrid gas turbine concentrated solar power systems

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Abstract

Utilities currently require fast-responding natural gas turbines to stabilize the variability of renewable energy sources. Efficiency gains can be made by integrating these units into concentrated solar power plants that use air Brayton cycles. Operation of these hybrid power plants requires a combustor capable of accepting the high temperature air leaving the receiver. However, the next generation of solar receivers are expected to reach temperatures outside the capability of any existing combustion system. Autoignition and flashback risks complicate the use of conventional lean premixed injectors that are important for maintaining low NO_x emissions. The challenge is particularly apparent when operating at part load conditions. A multibank micromix combustor is described that offers a potential solution to the high temperature challenges.

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Keywords: concentrated solar power (CSP); lean premix combustion; micromix combustion; part load turbine operation

1. Introduction

Utilities currently require fast-responding natural gas turbines (peaking units) to stabilize the variability of renewable energy sources. These turbines are typically located in completely separate installations from the renewable-based power plant. However, co-locating natural gas turbines with solar power plants offers advantages that may improve the economic viability of concentrated solar power (CSP) air Brayton systems. In addition to

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sharing common infrastructure, colocation boosts thermodynamic efficiency. Specifically, the gas-fired combustor increases the turbine inlet temperature beyond what is possible with current solar receivers. The higher firing temperature raises the efficiency of the cycle, increases the fraction of solar energy converted to electrical power, and thereby improves the productivity of the heliostat field.

The U.S. Department of Energy Sunshot Initiative seeks to make concentrated solar power cost competitive with traditional energy sources. Receiver temperatures of 1,000°C are required to meet the program's objectives. Allowable combustor inlet temperatures must similarly increase to maintain the advantages of colocation. As part of the SunShot program, Southwest Research Institute and Solar Turbines Incorporated are increasing hybrid turbine capabilities from 650°C to 1,000°C by the development of a MW-scale novel gas turbine combustor.

No combustor technology currently available is compatible with a 1,000ºC inlet air temperature. Autoignition and flashback risks challenge the use of conventional lean premixed injectors that are important for maintaining low NO_x emissions. As will be shown, it is difficult to manage these risks over the range of expected receiver outlet and power load conditions. This paper explores the airflow management issues encountered by a lean premixed injector in a high temperature CSP application and motivates the development of a multibank micromix injector.

Nomenclature

A_{inj}	Flow area of the injector mixing passage
$\dot{m}_{total}$	Total air mass flow through the air Brayton cycle
P	Combustor pressure
S_{flame}	Representative flame speed for a particular geometry and flow regime
S_L	Laminar flame speed
S_T	Turbulent flame speed
t_{delay}	Autoignition delay time
t_{res}	Premix injector residence time
T_{flame}	Combustor flame temperature
T_{inlet}	Combustor inlet temperature
$T_{turbine}$	Turbine inlet temperature
U_{inj}	Injector flow speed
x_{inj}	Fraction of total mass flow sent through the injector

2. Autoignition and flashback hazards

2.1. Autoignition and flashback

Autoignition is a phenomenon where a flammable mixture will ignite without an external heat source. The characteristic time for this process is known as the autoignition delay time and is a function of temperature, composition, and pressure. The stoichiometric autoignition delay time is shown for various hydrocarbon fuels in Fig. 1 [1,2]. Autoignition delay time decreases rapidly with temperature. For a conventional natural gas turbine with combustor inlet temperatures less than 650°C, the autoignition delay time is on the order of 250 ms or longer. This is an eternity compared to the residence time in conventional premix injectors. However, the autoignition delay becomes only 0.6 ms at a combustor inlet temperature of 1,000°C. The very short delay time increases the difficulty of achieving satisfactory mixing before prematurely igniting inside of the injector.

Similarly, flame speed increases with inlet air temperature. Based on chemical kinetic calculations using the GRI-Mech 3.0 mechanism [3] implemented in the Cantera modeling environment [4], the laminar flame speed for methane-air is approximately 20 times faster at 1,000ºC than at room temperature. An established flame can propagate upstream into the premix injector without autoignition if the turbulent flame speed exceeds the local flow speed. This phenomenon, known as flashback, becomes of increasing concern as the flame speed increases. Whether the root cause is autoignition or flashback, premature ignition inside the injector must be avoided because of its detrimental impact on injector life and NO_x emissions.

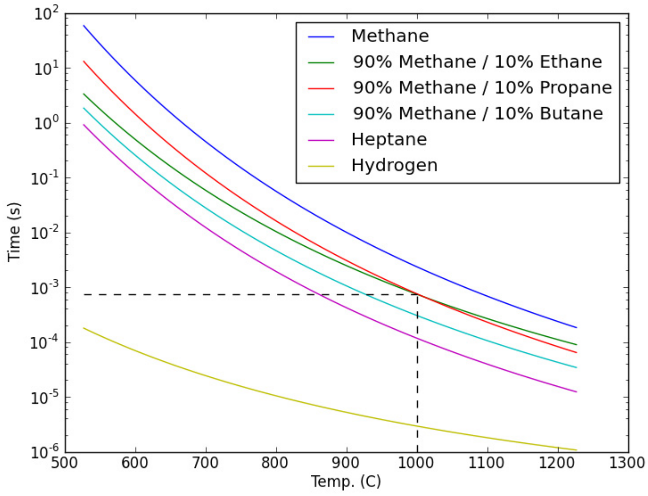

Fig. 1. Autoignition delay time vs. temperature for various fuels [1,2].

2.2. Serial vs. parallel configuration

Autoignition and flashback only influence the hybrid turbine combustor design if the inlet air temperature is elevated by the solar receiver. Rather than deal with the challenges of high combustor inlet temperature, the natural gas combustor may be placed in parallel with the solar receiver. The two possible configurations are shown schematically in Fig. 2. The combustor receives air at the cooler compressor discharge temperature where conventional combustor technology is adequate. The two hot gas streams then merge together before entering the turbine.

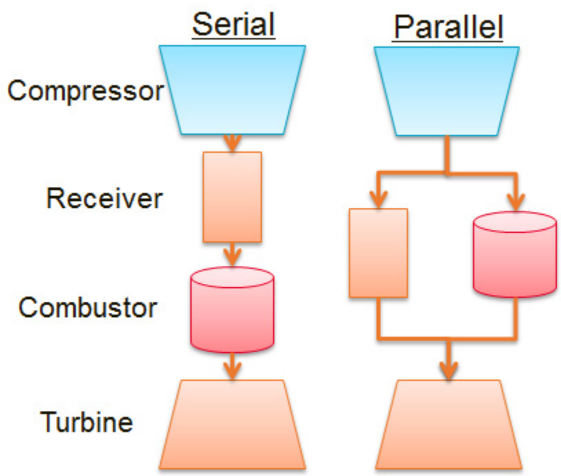

Fig. 2. Serial vs. parallel arrangement of the receiver and combustor.

The two configurations were compared on the basis of solar energy utilization and emissions as a function of the average combustor equivalence ratio. Results are shown in Fig. 3. Emissions were estimated using GRI-Mech 3.0 and Cantera assuming a combustor residence time of 4 ms. The receiver outlet temperature was set to 1,000°C and the turbine inlet temperature to 1,150°C. Note that CO emissions are too high for higher equivalence ratios because the single volume model did not account for the lower temperature transition region. However, the main conclusion is clear. A parallel configuration requires operating with a very high flame temperature in order to maximize the amount of solar energy utilized. Even so, it never reaches the solar fraction of the serial configuration. This can be understood by considering that every parcel of air must be heated from the compressor discharge temperature to the turbine inlet temperature. In both cases natural gas is used to raise the average temperature from the receiver exit temperature to the turbine inlet temperature. However, the parallel configuration must also use natural gas to raise the combustor stream from the compressor discharge temperature to the receiver inlet temperature. Minimization of this extra natural gas requires a low combustor mass flow and therefore a high combustor exit temperature.

Operating at a high equivalence ratio and therefore a high flame temperature has consequences on emissions. In particular, NO_x emissions grossly exceed 10 ppmv, a value achieved or beaten by current gas turbines such as the Mercury™ 50. Reaching the target emissions level requires operating at an equivalence ratio of 0.2-0.3. In this range the solar energy fraction for the parallel configuration is only 50-60% versus the serial's 80%. It is desired for a power station of a given capacity to be able to utilize as much solar power as possible. The autoignition and flashback challenges presented by the serial configuration are therefore worth tackling in order to achieve this advantage.

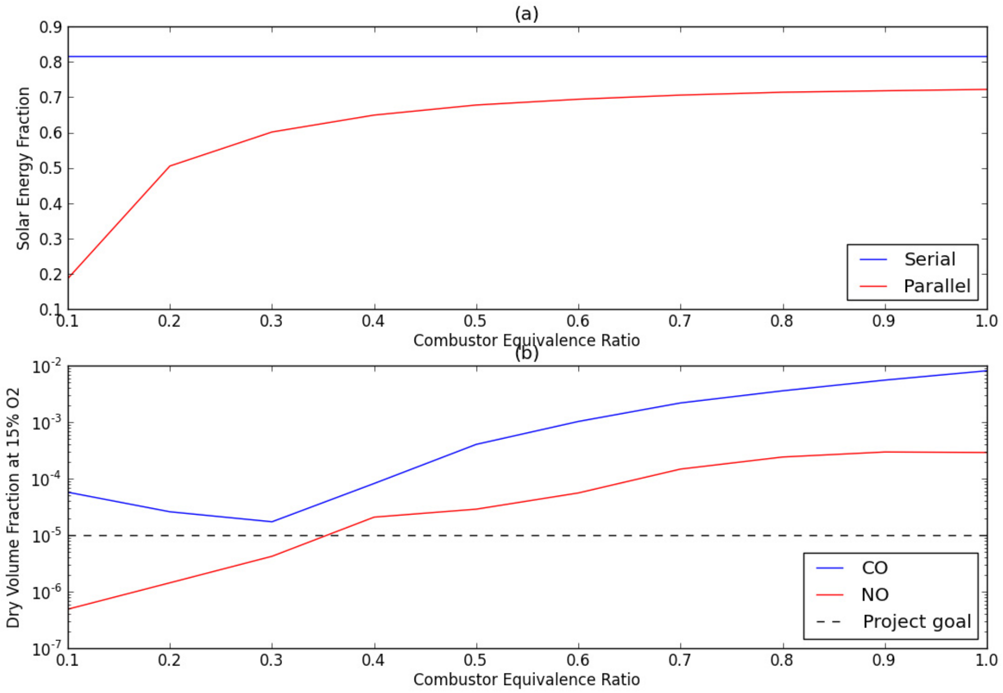

Fig. 3. (a) Solar energy fraction as a function of average combustor equivalence ratio (T_{inlet} = 1,000°C); (b) CO and NO emissions estimates as a function of average combustor equivalence ratio . (T_{inlet} = 1,000°C).

3. Design for variable load at high receiver temperatures

Autoignition and flashback phenomena become most apparent under part load conditions. To demonstrate this behavior, injector flow speed will first be selected for a notional design operating at 100% load, a turbine inlet temperature of 1,200ºC, and a combustor inlet temperature of 1,000 ºC. Scaling arguments will then be used to demonstrate how autoignition and flashback margin vary as the hybrid CSP system adapts to part load.

The design space for injector flow speed is shown in Fig. 4. The turbulent flame speed is plotted against the injector flow speed with both normalized by the laminar flame speed. Turbulent flame speeds are estimated using the Peters correlation for different assumed turbulence intensities [5]. The turbulence integral length scale was assumed to be 5e-03 m and the flame thickness to be 5e-05 m. Turbulent flame speed increases with flow velocity because of turbulent transport, but except for very slow flow speeds the flame speed is low enough that no flashback occurs. Injector flow speed is limited on the high end by the maximum allowable pressure drop, which is shown at the speed corresponding to 5% pressure loss.

In addition to the hard flashback boundary, there is also the soft constraint of the coupling effect. Ignition coupling occurs when the flow speed approaches the flame speed. One-dimensional flame simulations in Cantera were used to identify the effect, as shown in Fig. 5. In this scenario radicals are able to propagate upstream from the flame and thereby accelerate autoignition. This causes the observed time-of-flight autoignition delay time to decrease below the value expected from reported shock tube data. For enhanced margin it is also desired for an injector to operate outside of this range, which requires a flow speed of about 3 times the turbulent flame speed. A solution in the middle of the triangle of Fig. 4 appears to balance all of these requirements, giving a nominal injector flow speed of around 100 m/s at 100% load.

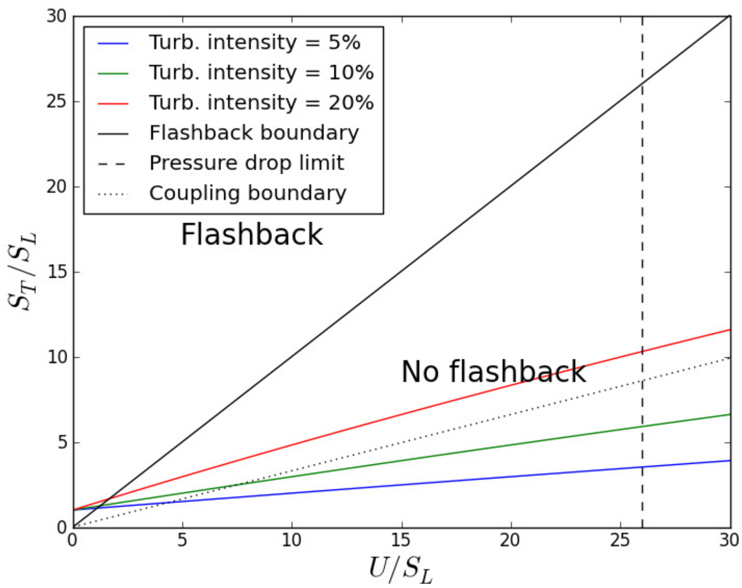

Fig. 4. Design space for the injector flow speed.

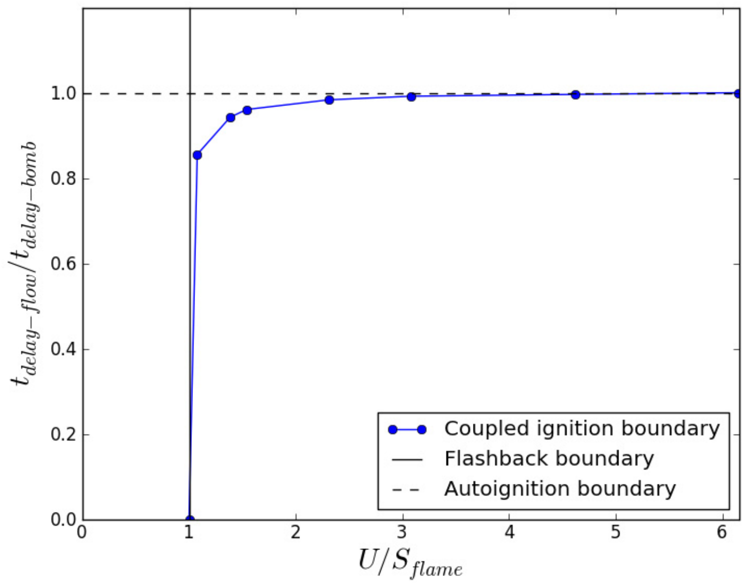

Fig. 5. Coupling of autoignition and flashback.

The injector flow speed scales according to the overall mass flow, fraction of air entering the injector, density of the air, and area of the injector, as shown in Eq. 1.

$$U_{inj} \propto \frac{x_{inj}\dot{m}_{total}}{A_{inj}} \frac{T_{inlet}}{P} \tag{1}$$

Assuming constant gas properties, the fraction of air entering the injector is fixed by the combustor inlet, turbine inlet, and flame temperatures, as shown in Eq. 2.

$$x_{inj} = \frac{T_{turbine} - T_{inlet}}{T_{flame} - T_{inlet}} \tag{2}$$

Combining these two gives Eq. 3. To further simplify the analysis, we assume the ratio of total mass flow to pressure remains constant across all load levels. We also assume a conventional bypass system that reroutes flow completely around the injector during part load and that the flow area in the premixing passage is fixed. The final injector flow velocity scaling is given by Eq. 4.

$$U_{inj} \propto \frac{\dot{m}_{total}}{A_{inj}} \frac{T_{inlet}}{P} \frac{T_{turbine} - T_{inlet}}{T_{flame} - T_{inlet}} \tag{3}$$

$$U_{inj} \propto T_{inlet} \frac{T_{turbine} - T_{inlet}}{T_{flame} - T_{inlet}} \tag{4}$$

Part load operation is achieved by a mixture of reducing mass flow, pressure, and turbine inlet temperature. Turbines vary in the combination they employ, but some drop in turbine inlet temperature is to be expected. Here we parametrically analyze what happens as a hypothetical turbine reduces its turbine inlet temperature from 1,200°C to 1,000°C and 800°C. The receiver temperature was allowed to go up to 1,000°C or the turbine inlet temperature, whichever was lower. Flashback margin for all three turbine inlet temperatures is shown in Fig. 6. The system operates as expected when the turbine inlet is 1,200°C. However, the situation changes as the turbine inlet temperature drops and approaches the receiver outlet temperature. In this case, there is a receiver temperature range over which the injector cannot operate without flashback. The blocked-out temperature segment can be up to 100°C in extent if some margin is desired.

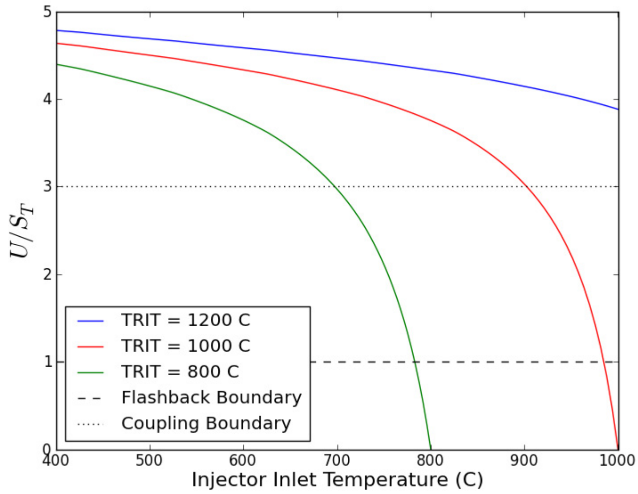

Fig. 6. Flashback margin as a function of injector inlet temperature for different turbine inlet temperatures.

The autoignition margin is shown in Fig. 7. For this plot it is assumed that the nominal injector achieves premixing just before autoignition. Injector velocity decreases and residence time increases as the turbine inlet temperature drops during part load operation. There is an approximately 70ºC wide receiver temperature segment that results in autoignition in the injector when the turbine inlet temperature is 1,000ºC. The affected segment for the 800ºC turbine inlet temperature is smaller because delay times increase as the inlet temperature decreases.

There appears to be a fundamental limitation on the part load operating range of a conventional lean premixed injector operating in a high temperature CSP application. Specifically, the injector becomes unable to operate safely as the turbine inlet temperature approaches the receiver outlet temperature. One may argue that the problem would be solved if the nominal design started with more margin. However, this is not a practical approach. Achieving mixing before autoignition with any margin at all is a significant challenge on its own when the delay time is 0.6 ms.

Expanding the lean pre-mix injector operating range requires a second consideration of Eq. 3. Previously we assumed the injector was of a fixed design; the flow area of the internal mixing passage could not be changed. The flow area we refer to here is not just the entrance or exit area, but the flow area over the entire length of the injector. If this overall flow area could be changed, then the injector velocity could be controlled and maintained above the critical value for part load condition for a broader range of receiver temperatures. The multibank micromix injector being developed under the SunShot Initiative provides this capability and is summarized in the next section.

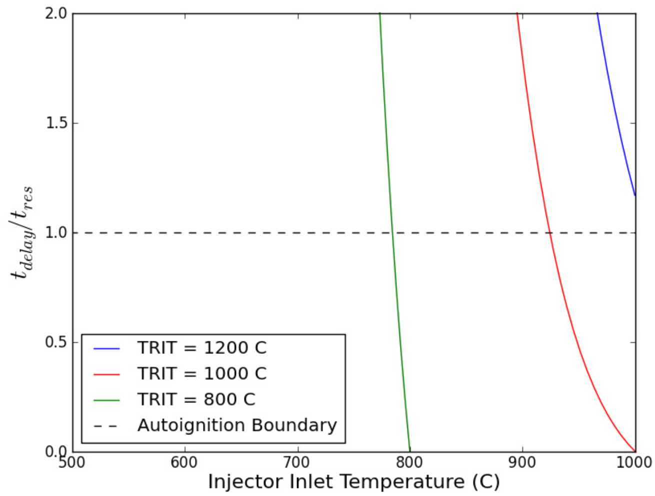

Fig. 7. Autoignition margin as a function of injector inlet temperature for different turbine inlet temperatures.

4. Multibank micromix design concept

An exploded view of the multibank micromix injector is shown in Fig. 8. Several small mixing passages are deployed in an array. These small mixing passages reduce the mixing length scale and thereby facilitate premixing before autoignition when operating at the highest inlet temperature. The other key design feature is the grouping of individual mixing passages into concentric banks that may be operated independently of one another. Air flows through all of the holes all of the time, but the controller selects which banks receive fuel for a given operating condition. Because of the mixing passageway spacing and high temperature of the incoming air, each hole is capable of supporting an individual flame even if the fuel to a neighboring hole is turned off. Nominally, the radially most inward bank is always on. Surrounding periphery banks are turned on as required.

In effect, periphery banks with fuel turned off are not functioning as part of the injector. Instead, they act as bypass channels that buffer the combustion liner from the full flame temperature. Selective bank operation allows the effective flow area of the injector to adapt to changing operating conditions, as shown schematically in Fig. 9. For varying load, this design architecture offers a solution to the autoignition problem identified in the previous section. For varying inlet temperature, the injector-integrated bypass concept allows for the maximum possible amount of cooling when operating with 1,000°C combustor inlet air.

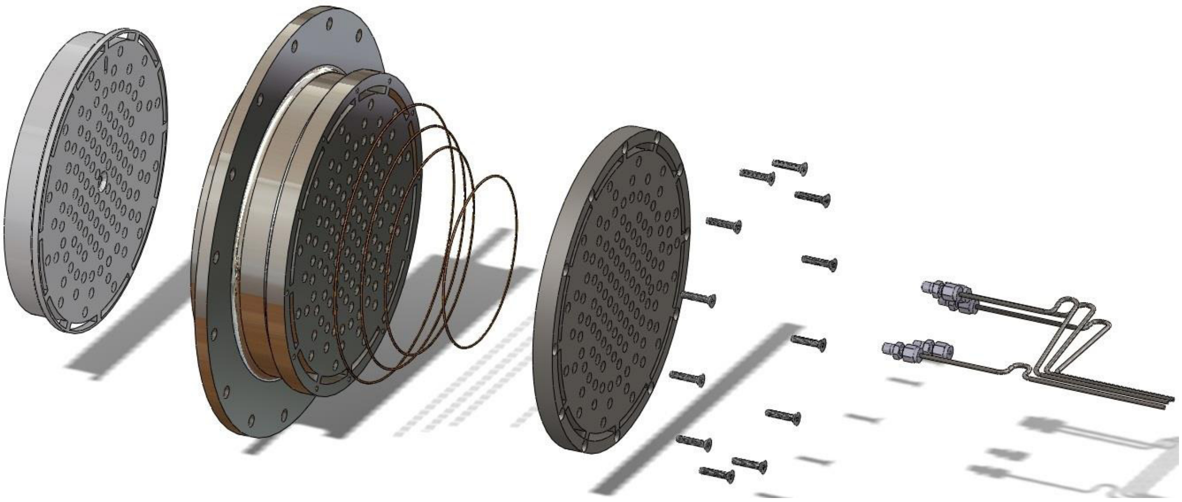

Fig. 8. Multibank micromix injector design.

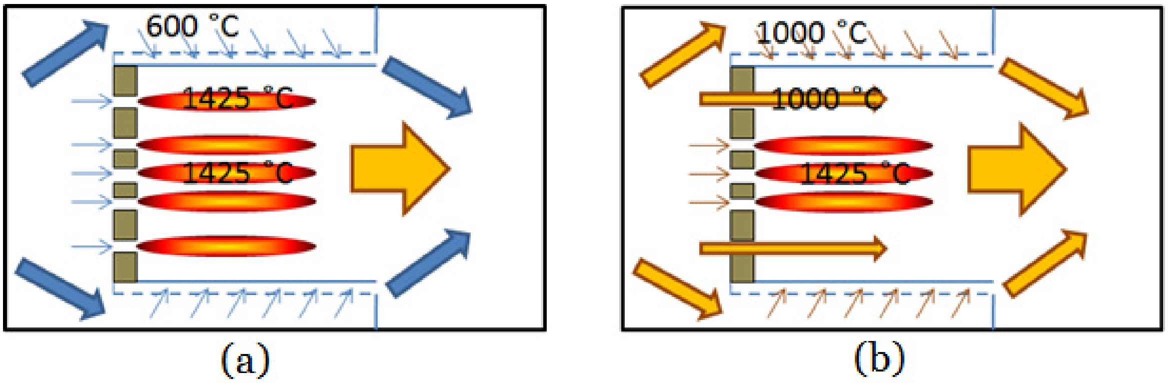

Fig. 9. (a) Schematic of multibank micromix injector design with 600°C inlet air. (b) Schematic of multibank micromix injector design with 1,000°C inlet air.

5. Concluding remarks

Autoignition and flashback pose serious design challenges to lean premix injectors operating in high temperature hybrid CSP power plants. These challenges are formidable at full load but become even more significant during part load operation. The multibank micromix injector being developed by Southwest Research Institute and Solar Turbines Incorporated reduces mixing length to achieve lean premixing without autoignition. Furthermore, the multibank design adaptively manages injector area to enable better part load operation with high receiver temperatures.

The detailed design of the multibank micromix injector is ongoing as part of the SunShot program, and prototype testing is expected to commence in 2014.

Acknowledgements

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